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This report addresses the design and operational concepts of an expendable 5 pound payload for a high altitude balloon or unmanned air vehicle. This payload consists of antenna, battery, and electronics and will serve as a satellite surrogate to provide communications in the UHF frequency band using existing off the shelf UHF radios. The transponder is an 18 MHz wideband architecture which will enable spread spectrums techniques as well as standard UHF narrow band communications. The payload is designed to operate at altitudes from 10,000' to 100,000' providing communications services within a 150 nmi radius for a duration in excess of 30 hours.

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In the report we show a maximum aggregate throughput of 1.2 Mbps at a 30,000' altitude and 140 kbps at an altitude of 100,000'. We also present two effective power control techniques that enable this throughput be achieved. This throughput can result in well over 100 narrowband users. The report is organized as follows. Section 1 is a brief introduction. Section 2 dicusses the architectural design and the operational requirements that influence the design. Section 3 presents the design details, tradeoffs, and analysis that were performed during the design. Section 4 discusses the operational concepts and the power control techniques to be employed.

Table of Contents

1. Introduction

This report describes the design of a 5 lb payload to be used as a UHF satellite surrogate with high altitude balloons or Unmanned Air Vehicles. Within the report is a detailed design description of the payload antenna, diplexor, and electronics. Following the design details, operational information and concepts are presented. An analysis of system capacity as well as power control techniques that realize this capacity are described. At the conclusion of the report several examples on network planning, consisting of mission planning, parameter assignment, and power allocation, are presented along with the associated link budgets.

2. Architectural Design

The major architectural tradeoff in the payload design is that of a wideband transponder vs. a channelized transponder. This section of the report defines the operational requirements and how they influence the resulting architecture of the payload.

2.1. Operational Requirements

Operationally, it is desired that the 5 lb payload be designed to operate with Unmanned Air vehicles (UAV's) and stable balloons. Some desired characteristics of the balloon/ UAV communication systems are listed below:

- Support up to 100 simultaneous users
- Operate altitudes from 10,000 ft to 100,000 ft
- Have a lifetime > 24 hours
- Operate with existing UHF radios

2.2. Frequency Plan

We have chosen a frequency plan similar to that of UHF satellites. This uplink frequency band will be ≈ 292 - 311 MHz, and the downlink frequency shall be ≈ 252 - 270 MHz. The payload will provide a 41 MHz frequency translation. This frequency plan will allow operation with standard UHF radios. Such radios include, but are not limited to:

- AN/PSC-3 manpacks
- HST-4 manpacks
- LST-5 manpacks
- AN/ARC-187 airborne terminals
- URC-100 series shipboard terminals
- AN/WSC-3 shipboard terminals
- AN/SSR-1 shipboard terminals

The selected frequency bands also overlap the 25 kHz channels of the existing FLTSATCOM satellites. The FLTSATCOM frequency plan is presented below in table 2.2-1.

Channel	Plan	Downlink Freq (MHz)	Uplink Freq (MHz)	Bandwidth (kHz)
2	A	251.95	292.95	25
	B	252.05	293.05	25
	C	252.15	293.15	25
3	A	252.65	293.65	25
	B	252.75	293.75	25
	C	252.85	293.85	25
4	A	255.35	296.35	25
	B	255.45	296.45	25
	C	255.55	296.55	25
5	A	256.95	297.95	25
	B	257.05	298.05	25
	C	257.15	298.15	25
6	A	258.45	299.45	25
	B	258.55	299.55	25
	C	258.65	299.65	25
7	A	265.35	306.35	25
	B	265.45	306.45	25
	C	265.55	306.55	25
8	A	266.85	307.85	25
	B	266.95	307.95	25
	C	267.05	308.05	25
9	A	268.25	309.25	25
	B	268.35	309.35	25
	C	268.45	309.45	25
10	A	269.75	310.75	25
	B	269.85	310.85	25
	C	269.95	310.95	25

Table 2.2-1. FLTSATCOM 25 kHz Channels Frequency Plan

One problem to be addressed is the peaceful coexistence of our users with FLTSATCOM or other UHF satellites users in the same geographical vicinity. Our approach is to only use frequencies that aren't used by other UHF satellites. As an example, the FLTSATCOM channels in table 2.2-1 are 25 kHz wide. There are a total of 27 channels in this frequency band, using a total of 675 kHz. The transponder allocated bandwidth is ≈ 18 MHz, thus 96% of the frequency plan is not used by FLTSATCOM. Similarly one could avoid the channes occupied by other UHF satellites in the vicinity.

FLTSATCOM channels exist on a frequency plan (A, B or C). A single FLTSATCOM satellite will only use one of these frequency plans at one time. This is allows adjacent satellites to operate with different frequency plans. This way the channel 2 (or any other channel) downlinks from adjacent satellites will not interfere with each other in the common area of the two satellite footprints. The frequency plans will also allow us to use frequencies that occupy a FLTSATCOM, or other UHF satellite, channel. This is accomplished by using a frequency plan (A, B, or C) not currently operating within the satellite(s) in view.

2.3. Receive Level Analysis

This section provides a preliminary analysis of the received signal level at the payload receive antenna output. This analysis will be useful in the understanding the tradeoffs involved section in 2.4, wideband vs channelized architecture.

The received signal level will be a function of the following:

- Ground station EIRP. The analysis assumes a ground station Tx antenna gain of 6 dBi and is performed with power amplifier sizes of 1 Watt and 100 Watts.
- Payload Rx antenna gain. For the analysis, we have assumed a Rx antenna gain of 0 dBi in all directions. The actual Rx antenna will have differing gains at different directions. The impact of this will be determined in section 3.1-1.
- System Geometry consisting of payload altitude and elevation angle to the payload. These two items uniquely determine the propagation distance. Knowledge of the transmit frequency and the propagation distance uniquely determine the propagation loss.

The analysis is performed at a frequency of 300 MHz. The results are shown below in table 2.3-1.

Altitude	Coverage Radius	Received Levels 1 Watt Tx	100 Watt Tx
10,000 ft	18.4 nmi	-77 to -57 dBm	-57 to -37 dBm
30,000 ft	52.4 nmi	-86 to -65 dBm	-66 to -46 dBm
70,000 ft	111.8 nmi	-92 to -73 dBm	-72 to -53 dBm
100,000 ft	151.2 nmi	-95 to -76 dBm	-75 to -56 dBm

Table 2.3-1. Received Signal Levels

The received levels, at a particular altitude and transmit power, vary from the minimum level at an elevation angle of 5° to the maximum level at an elevation angle of 90°. The important result of this analysis is that it identifies a received signal level dynamic range of 58 dB (minimum signal level of -95 dBm, maximum signal level of -37 dBm).

2.4. Wideband vs. Channelized

The major architectural issue involved in the design of the payload is the use of a wideband or channelized transponder. A wideband transponder consists of amplification and frequency translation for the entire bandwidth identified in section 2.2. All FDMA users are amplified and frequency translated together. A simplistic block diagram for a wideband approach is shown in figure 2.4-1. Wideband transponders are very common at microwave frequencies. Examples of such transponders are DSCS-II, DSCS-III, NATO-III, Nato-IV, and Skynet-4.

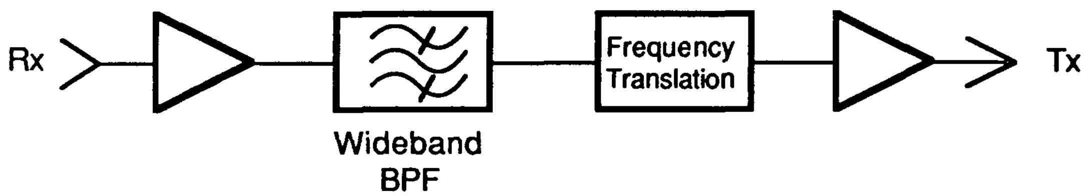


Figure 2.4-1. Wideband Transponder Architecture

A channelized transponder would consist of a separate narrowband channel for each user. Each channel is separately amplified and filtered. Examples of channelized transponders include the narrowband channels on FLSTSATCOM, LEASAT, and GAPFILLER.

The advantage of the channelized approach is that it completely eliminates the received signal dynamic range problem and allows one to accurately set the transponder transmit power. These properties are a result of a limiter and narrowband filter incorporated within each channel (see figure 2.4-2 below). The ground transmitter must transmit enough power such the the SNR out of the narrowband bandpass filter is greater than 1 (preferably much greater than 1). Any transmit power above this threshold is acceptable. After the limiter, the signal is at a known power level, determined by the limiter level. Combining with other channels, frequency translation, and fixed amplification yields a fixed known transponder output level, as long as the ground transmitter EIRP is above a predetermined threshold.

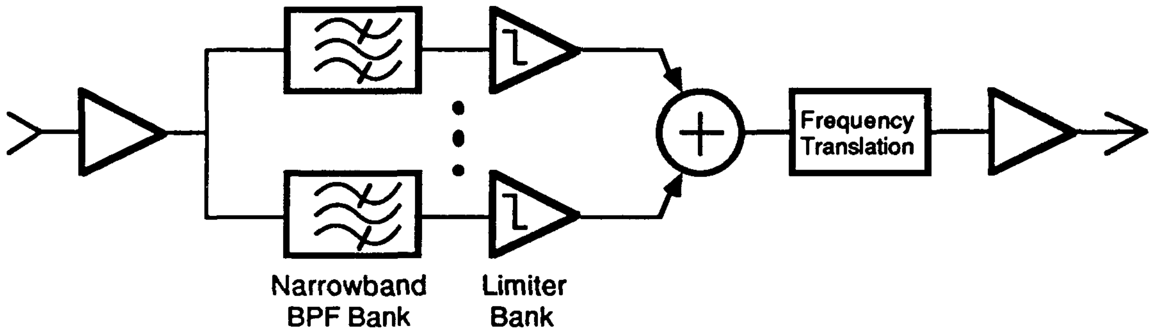


Figure 2.4-2. Channelized Transponder Architecture

The disadvantage of channelization is the hardware complexity. We estimate that only several channels could be provided while staying within a 5 lb payload weight limit. On the other hand, the only limit to the number of users with a wideband approach is the available bandwidth and power. We shall show in section 4, System Analysis, that there is sufficient bandwidth and power to support more than 100 users.

The drawback to a wideband approach is the issues involved with setting up a link. This is a direct result of the large dynamic range of the received input signal level and the fact that the transponder should be operated in its linear region. If the level of one of links (or the total power of the sum of all the links) is large enough to cause the transponder to operate in its nonlinear region, many intermodulation products would result. These intermodulation products may be located at the same frequency as some of the users, interfering with or jamming many links. One possible approach to this problem is to design the transponder net electronic gain such that the largest input signal level, -37 dBm from table 2.3-1, is still not large enough to cause non-linear operation. But then the transponder output power that the smallest signal level, -95 dBm, could reach would be 58 dB below the maximum output power. For an estimated +10 dBm maximum transponder output power, the worst case -48 dBm output power level is not sufficient to support any communications. Thus the transponder electronic gain must be set large enough to allow the worst case users some communication capabiality, in which case, the best case users will be capable of forcing the transponder into a nonlinear operating region.

Based upon the requirement to support up to 100 of users, we have selected a wideband approach. We will use following three techniques to prevent non-linear operation and still enable communications for the worst case users.

- Antenna design to produce more gain at the horizon and less gain at boresight. This reduces the dynamic range due to elevation angle variation. details on the antenna performance are provided in section 3.1.
- Programmable fixed gain states within the transponder. This allows transponders that will operate at higher altitudes to have more electronic gain that those that will operate at lower altitudes. The selection of the gain state is based upon the payload altitude and the planned transmit power of the ground transmitters. The electronic details of the gain states are presented in section 3.3 while the operational aspects are presented in section 4.3.
- Use of power control to set the ground transmit power to the proper level. This is discussed in section 4.1.

The selected wideband also has the advantage of large channel bandwidth. This will allow use higher data rates, frequency hopped, or direct sequence spread spectrum systems. The spread spectrum techniques might be used to implement a low probability of intercept (LPI) or anti-jam system.

3. Payload Detailed Design

Figure 3-1 shows a simplistic block diagram of the transponder depicting the major functional blocks. The design details of the antenna, diplexor, and electronics are discussed in sections 3.1 thru 3.3. The performance analysis and tradeoff studies performed in the design of the transponder are described in section 3.4. Mechanical data is presented in section 3.5.

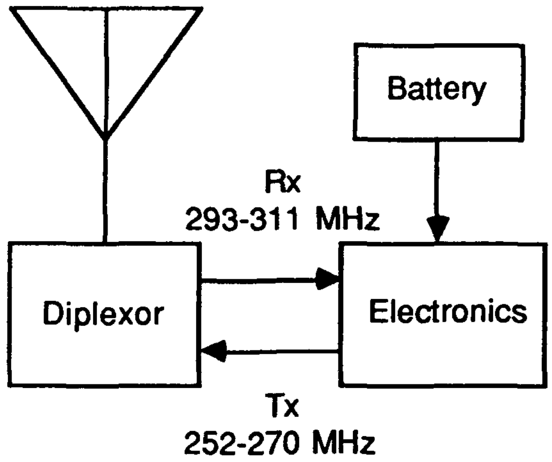


Figure 3-1. Transponder Block Diagram

3.1. Antenna

One of the main objectives of the antenna design is to provide more gain on the horizon than at boresight (looking straight down). This larger gain at the horizon will counteract the larger path loss on the horizon thus reduces the dynamic range of the received signal. The other main objective is to be small and light weight. Other requirements include an operating frequency range of 252 to 311 MHz and polarization as to enable operation with circularly polarized ground antennas.

To achieve the aforementioned objectives we have selected a Vertically Oriented 1/2 Wave Dipole. The geometry for the half wave dipole is shown in figure 3.1-1. Note that the angle defined as θ in the figure is also the elevation angle for ground station.

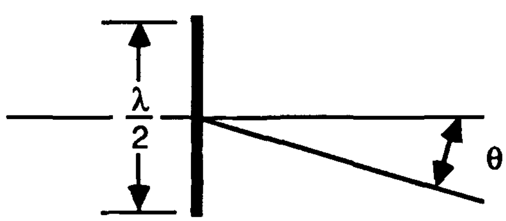


Figure 3.1-1. Half Wave Dipole Antenna Geometry

The half wave dipole has a maximum gain of 2.15 dB, at an angle $\theta = 0°$, and has fixed gain as a function of azimuth angle. The gain as a function of elevation angle, θ, is given by,

$$\text{Gain} = 2.15 + 20 \cdot \text{Log}_{10}\left\{\frac{\cos(\pi/2 * \cos\theta)}{\sin\theta}\right\} \text{ dB} \tag{3-1}$$

A plot of this gain variation is shown in figure 3.1-2. In theory this antenna has zero gain ($-\infty$ dBi) at an angle θ =90°, but in practice this null depth is never achieved. A realistic null depth for this point is -20 dBi, thus this is the value we shall use for the 90° elevation angle.

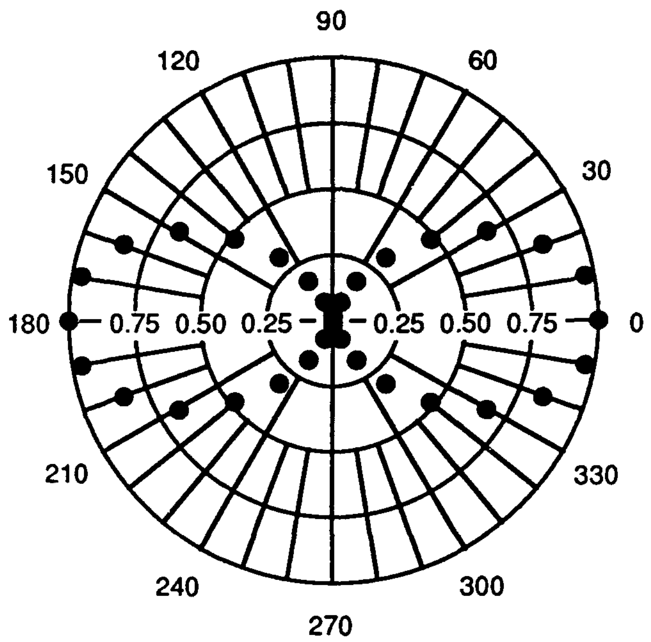


Figure 3.1-2. Half Wave Dipole Gain Pattern.

The combined effect of the additional path loss (path loss above the path loss experienced at an elevation angle of 90°), as a function of θ and the antenna gain reduction as a function of θ is shown in figure 3.1-3. The combined effect is shown as the square points on the curve. This curve was generated for a transponder altitude of 70,000'. As can be seen, the antenna reduces the received signal level dynamic range by 5 dB.

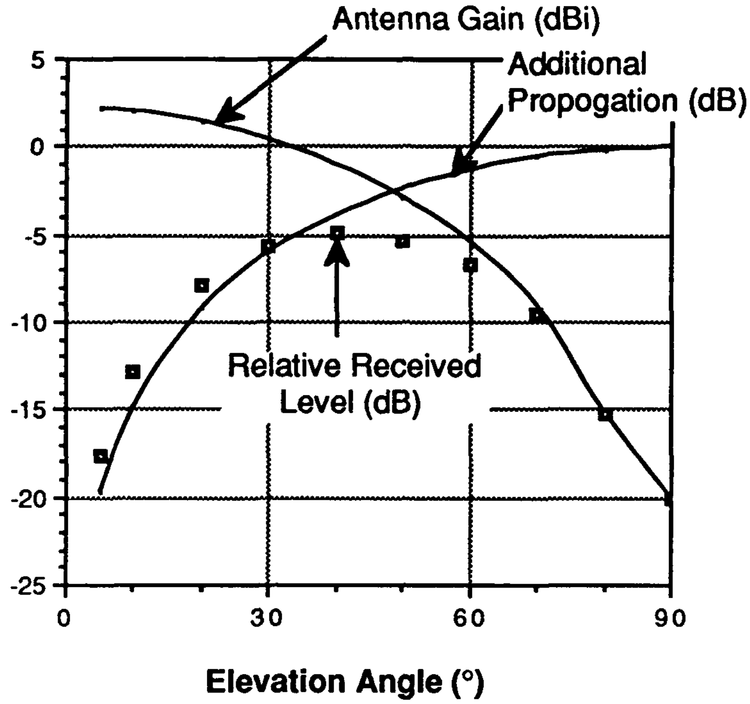


Figure 3.1-3. Combined Effects of Antenna and Path Distance

The half wave dipole is linearly polarized. When it is vertically oriented, the magnetic field lies entirely in horizontal plane. Thus use of a circularly polarized antenna on the other side of the link will result in a 3 dB polarization loss independent of the type of circular polarization (RHCP or LHCP). This loss will also remain the same for any orientation of the transponder antenna.

Using the previous antenna gain characteristics and a diplexor insertion loss of 1.5 dB, the analysis of section 2.3 can be repeated generating the received signal levels in table 3.1-1 below. These are the signal levels into the transponder electronics using a ground transmit antenna of circular polarization and 6 dBi gain.

Altitude	Coverage Radius	Received Levels 1 Watt Tx	100 Watt Tx
10,000 ft	18.4 nmi	-80 to -65 dBm	-60 to -45 dBm
30,000 ft	52.4 nmi	-90 to -75 dBm	-70 to -55 dBm
70,000 ft	111.8 nmi	-97 to -82 dBm	-77 to -62 dBm
100,000 ft	151.2 nmi	-100 to -85 dBm	-80 to -65 dBm

Table 3.1-1. Received Signal Levels into Electronics

A typical half wave dipole antenna in this frequency range, weighs less than 0.50 lbs and is ≈ 15 inches in length. An off the shelf antenna half wave dipole that operates in the 329 to 336 MHz range is Trivec Avant P/N 44-70-01. This antenna would be ideal except for the frequency range. Discussion with the potential antenna vendors led to the following antenna specifications for the transponder half wave dipole.

Type:	Half Wave Dipole
Frequency:	252 to 311 MHz
Impedance:	50Ω
VSWR:	3.0:1
Peak Gain:	2.1 dBi
Weight:	< 0.5 lbs

Table 3.1-2. Antenna Specifications

3.2. Diplexor

The diplexor is a three port device that connects to the antenna, the transmitter, and the receiver. Ideally, all of the power received at the antenna port should couple to the receiver port and all of the power presented to the transmit port should couple to the antenna port. However, in practice, most of the power is coupled to the desired port, some of the power is dissipated within the device, and some of the power is coupled to the isolated port. The dissipated power is characterized by the insertion loss, and the power coupled to the isolated port is characterized by the isolation. The most important isolation parameter is the isolation between the transmit port and the receive port.

We have selected a diplexor manufactured by Lark Engineering. Its is based upon two bandpass filters combined in a way to generate the desired 3 port diplexor. The bandpass filters used are Lark Eng P/N DP-302-26-6MM (receive filter) and DP-261-18-6AA (transmit filter). The characteristics of the resultant diplexor is shown below.

Insertion Loss:	≤1.5 dB
1 dB Bandwidth:	294.5 -309.5 MHz (Tx)
	253.5 -268.5 MHz (Rx)
3 dB Bandwidth:	252 - 270 MHz (Tx)
	293 - 311 MHz (Rx)
Tx - Rx Isolation[1]:	> 63 dB (f<270 MHz)
	61 dB (f=270 MHz)
	73 dB (f=281.5 MHz)
	67 dB (f=293 MHz)
Size:	1 x 3 x 5"
Weight:	< 1 lb

Table 3.2-1. Diplexor Characteristics

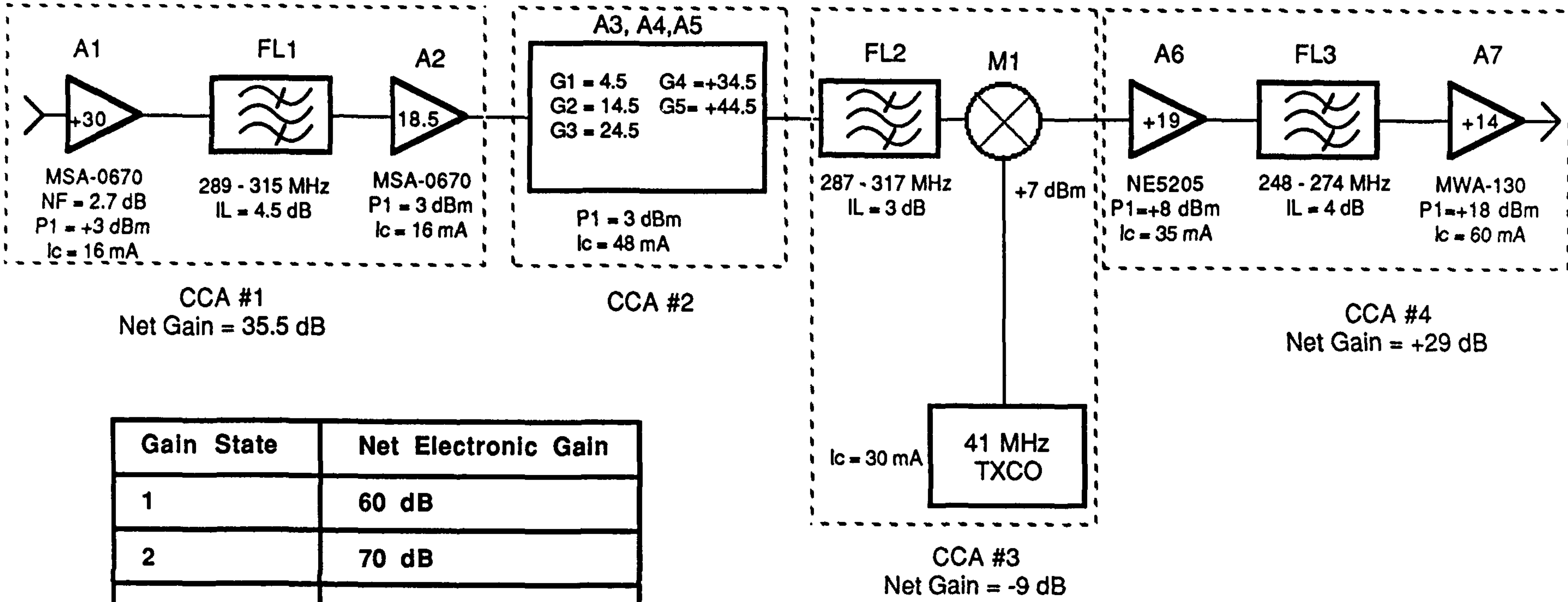
3.3. Electronic Design

3.3.1. Design Overview

A functional block diagram of the transponder electronics is shown in figure 3.3-1. The figure identifies critical parameters: net gains, insertion losses (IL), applicable noise figures (NF), output 1 dB compression points (P1), current draw (Ic), and filter 3 dB bandwidths. The design provides for 5 different gain states, providing net gain from 40 to 100 dB in increments of 10 dB. These different gain states allow for the selection of the optimum transponder net gain based upon planned transponder altitude and planned ground terminal transmit EIRP.

In section 3.4.1 of this report we show that the maximum output level of transponder electronics is ≈+18 dBm. When the output power is at this maximum the transponder is in a nonlinear state. To operate the transponder linearly, the output should be backed off about 3-6 dB. The actual amount depends upon the level of intermodulation products which is acceptable which, in turn, depends upon the level and frequency of the actual users. For analysis purposes, we shall defined the transponder as being sufficiently linear whenever the total output power is ≤ +12 dBm (6 dB output backoff) out of the electronics.

[1] Here the isolation is the result of four effects: the insertion loss on the transmit side, the insertion loss on the receive side, the rejection of the transmit filter, and the rejection of the receive filter.



Gain State	Net Electronic Gain
1	60 dB
2	70 dB
3	80 dB
4	90 dB
5	100 dB

Figure 3.3.1-1. Electronics Block Diagram

When the transponder is non-linear, the majority of the non-linearities occur in the amplifiers A7, A6, and A5. The filters FL2 and FL3 are used to reject the out of band intermodulation products generated by the non-linearities. This prevents them from generating more inband intermodulation products within the downstream non-linearities. As an example consider two tones at 300 and 301 MHz as an input to A5 which is operating with severe non-linearities. In band, third order intermodulation products (IM products) will be generated at 299 (3x300 - 301) and 302 (3x301 - 300) MHz. Out of band, second order IM products will be generated at 600, 601, and 602 MHz. With the filter present, theses out of band IM products are removed. If A6 is operating non-linearly, the dominant inband third order IM products on the output of A6 occur at 297, 298, 299, 300, 301, 302, 303, 304, and 305 MHz. Without the filter present, these third order IM products still occur, but additional dominant second order IM products occur at 299, 300, 301, and 302 MHz. These additional second order products can be larger than the existing third order products thus increasing the level of the intermodulation products.

Included within the figure 3.3-1 is the partitioning of the electronics into 4 circuit card assemblies (CCA's). Each CCA is located within it's own shielded enclosure. This physical isolation needs to be provided to prevent excessive electromagnetic interference (EMI), either conducted or radiated, from one part of the circuit to another. There are three major guidelines that led to the resultant partitioning. First, keep the net gain of any one CCA below 50 dB. This will help prevent self oscillation (see section 3.4.1, stability analysis). Second, don't put more than one filter within a module. The total sum rejection of multiple filters within a module will almost always be less than the sum of the individual specifications. This is because the suppression of the radiated and conducted interference will be less than the rejection of the filter. Placing filters in different modules increases the EMI suppression due to the physical shielding, thus enabling the total filter rejection to be the sum of both filters. The third guideline is the keep the high level LO circuitry within it's own module. This reduces the amount of radiation and conduction of the high level LO to the more sensitive part of the circuitry.

3.3.2. CCA Description

The first CCA, the LNA CCA, provides low noise amplification and bandpass filtering. The amplifiers selected are Avantek Monolithic Microwave Integrated Circuits (MMIC's). The noise figure of amplifier A1 determines the transponder noise figure of 2.7 dB. For the link budgets presented in section 4, we shall use a noise figure of 3 dB as well as a diplexor insertion loss of 1.5 dB. The bandpass filter selected is Lark Engineering P/N

TC-302-26-6MM. The characteristics of this filter are described below. The size of this circuit board is 0.75" x 1.25".

Insertion Loss:	< 4.5 dB
3 dB BW:	289 - 315 MHz
1 dB BW:	293 - 311 MHz
20 dB points:	283 MHz, 326 MHz
40 dB points:	270 MHz, 339 MHz
60 dB points:	254 MHz, 365 MHz
Size:	.60" x .35" (Dia x Height)
Weight:	0.25 oz

Table 3.3.2-1. FL1 Filter Characteristics

CCA #2, the gain state CCA, consist of the 5 different programmable gain states. The gain state for the CCA is selected via a dip switch located on the CCA. Block diagrams of the 5 different gain states are shown in figure 3.3.2-1a thru 3.3.2-1e. The amplifiers used in the CCA are Avantek MMIC's. The size of this CCA is 3.75" x 2.75".

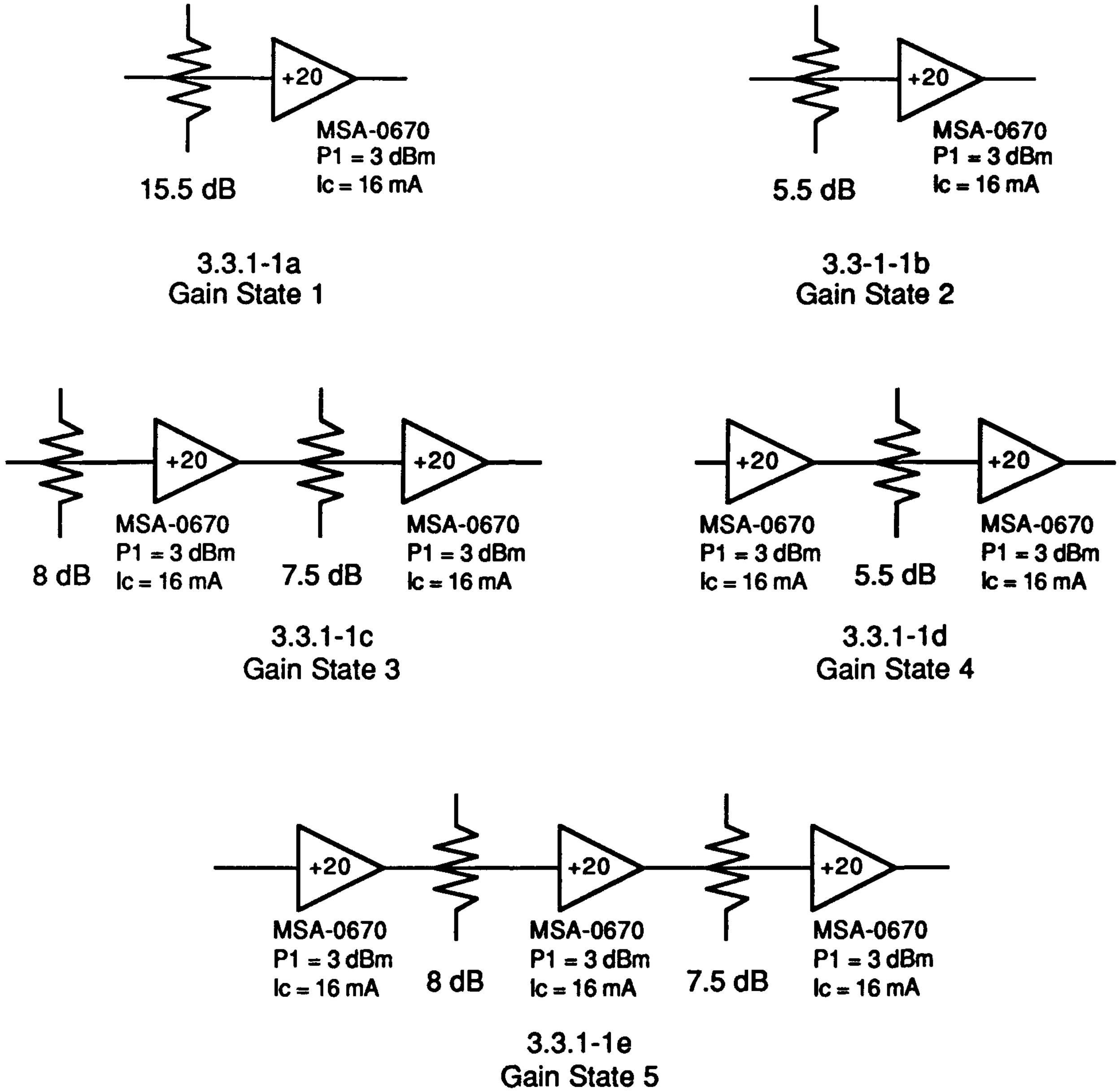


Figure 3.3.2-1. Gain State Block Diagrams

CCA #3, frequency translation CCA, provides the frequency translation. The bandpass filter is a Lark Eng. P/N TC-302-30-4MM. The characteristics of the filter are shown in table 3.3.2-2. The mixer is a standard +7 dBm LO drive mixer. The local oscillator is a TCXO, Vectron P/N C0-254F26 except 8 VDC supply and sinewave output. Specifications for the TCXO are shown in table 3.3.2-3. The temperature stability of the oscillator, 2×10^{-6}, yields a worst case frequency translation error of 82 Hz. The size of this CCA is 2.25" x 4.75".

Insertion Loss:	< 3.0 dB
3 dB BW:	287 - 317 MHz
1 dB BW:	291 - 313 MHz
20 dB points:	272 MHz, 338 MHz
40 dB points:	248 MHz, 374 MHz
60 dB points:	233 MHz, 410 MHz
Size:	.60" x .35" (Dia x Height)
Weight:	0.25 oz

Table 3.3.2-3. FL2 Filter Characteristics

Frequency:	41.0 MHz
Output:	+7 dBm sinewave, 50Ω
Temperature Stability:	$\pm 2 \times 10^{-6}$
Aging	2×10^{-6}/yr
Frequency Adjustment:	Sufficient to compensate for 5-10 years of aging
Temperature Range:	-55°F to +85°F
Supply Voltage:	+8V
Current Draw:	<30 ma
Size:	2" x 2" x 3/4"
Weight:	3 oz

Table 3.3.2-3. TCXO Specifications

CCA #4 , output CCA, provides output filtering and final amplification. The amplifiers used are a Signetics NE5205 and Motorola MWA-130. The bandpass filter used is a Lark Eng. P/N TC-261-26-6MM. The characteristics of this filter are described in table 3.3.2-3. The size of this is 0.75" x 1.25".

Insertion Loss:	< 4.0 dB
3 dB BW:	248 - 274 MHz
1 dB BW:	252 - 270 MHz
20 dB points:	243 MHz, 285 MHz
40 dB points:	230 MHz, 298 MHz
60 dB points:	213 MHz, 324 MHz
Size:	.60" x .35" (Dia x Height)
Weight:	0.25 oz

Table 3.3.2-3. FL3 Filter Characteristics

3.4. Analysis and Tradeoff Studies

3.4.1. Gain and Level Analysis

Due to the large amount of electronic gain within the transponder, 100 dB at gain state 5, there are 3 design constraints involving saturation of one or more of the amplifiers:

1) We do not want the transponder to saturate due to thermal noise alone.

2) We do not want the transponder to saturate on the transmitted signal that leaks through the diplexor and into the receiver.

3) When there is a received signal large enough to cause saturation in the transponder, we want to understand exactly how and where it saturates. Thus it saturates in a controlled fashion and one can predict what the intermodulation products will be. Also, by placing a bandpass filter immediately after the non-linearities, one can minimize the levels of the in-band intermodulation products generated.

Table 3.4.1-1 presents the analysis that addresses these concerns for gain state #5. The first five columns of the table identify the reference designator, part number, net gain, 3 dB bandwidth, and output 1 dB compression point of each component within the transponder electronics. The sixth column (Cum. Gain) shows the computed cumulative net gain. The seventh column (Equivalent Max Input) shows the level of the input signal which will cause that particular component to be operating at its output one dB compression point assuming all the components before it are linear. This result addresses concern number 3. That is, the row that has the smallest Equivalent Max input number, contains the component that will first start to behave non-linearly. As can be seen in table 3.4.1-1, the output amplifiers A6 and A7 will become the first amplifiers to become non-linear. When the input signal is sufficiently below ≈-82 dBm, the transponder is essentially linear. As the input signal increases to near-82 dBm, the transponder will start to behave non-linearly at the the amplifiers A6 and A7. As it increase to near -77 dBm, the amplifier A5 will start to behave non-linearly.

Item	Part No.	Net Gain (dB)	Output P-1dB (dBm)	BW (MHz)	Cum. Gain (dB)	Equivalent Maximum Input (dBm)	Noise Level (dBm)	Max Tx Level (dBm)
A1	MSA-0670	20	3	1000	20	-17	-61	-23
FL1	TC-302-26-6MM	-4.5	29.5	26	15.5	14	-81	-68
A2	MSA-0670	20	3	1000	35.5	-33	-61	-48
A3	MSA-0670	20	3	1000	55.5	-53	-41	-28
Pad 1	8 dB	-8	22	1000	47.5	-26	-49	-36
A4	MSA-0670	20	3	1000	67.5	-65	-29	-16
Pad 2	7.5 dB	-7.5	22.5	1000	60	-38	-36	-23
A5	MSA-0670	20	3	500	80	-77	-16	-3
FL2	TC-302-30-4MM	-3	30	30	77	-47	-19	-26
M1	SBL-1	-6	-5	1000	71	-76	-25	-32
A6	NE5205	19	8	500	90	-82	-6	-53
FL3	TC-261-26-6MM	-4	29	26	86	-57	-10	-57
A7	MWA-130	14	18	500	100	-82	4	-43

Table 3.4.1-1. Gain State 5 Level Analysis

The eight column (noise level) indicates the total noise power out of each particular component. Thus is computed based upon a input sky noise level of -174 dBm/Hz, a noise figure of 3.5 dB, and the minimum bandwidth of all the components preceding it. To prevent non-linearities based upon the noise alone, all noise power outputs should be below the corresponding output 1 dB compression point.

The last column (max Tx Level) indicates the level of the transmitted signal that leaks through the diplexor. For example a maximum output transmit signal of +18 dBm at 270 MHz results in a received input signal of -43 dBm at 270 MHz. That is because of 61 dB isolation provided by diplexor at 270 MHz. Thus the output of the first amplifier is -23 dBm. To insure that this signal doesn't cause any non-linearities, the outputs must be below the corresponding 1 dB compression points.

To estimate the maximum electronics output power, consider an input signal much greater than -77 dBm. The amplifier, A5 will be heavily saturated. Typically the saturated output power is ≈ 2 dB above the amplifier 1 dB compression point. Thus the level out of A5 will be ≈+5 dBm. The net gain to the output of A6 is 10 dB, thus the level out of A5 would be +15 dBm if A5 were linear. Since the 1 dB compression point of A5 is +8 dBm, it is definitely not linear. However, it is also not in deep saturation (which would produce an ≈+10 dBm output), therefore the output level of A5 will be between +8 and +10 dBm, say ≈+9 dBm. The net gain from A6 output to A7 output is 10 dB, so the transponder output would be +19 dBm if A7 were linear. But it also is non-linear at this level. In fact the output signal will be compressed by exactly 1 dB at the output of A7, thus the maximum signal out of the transponder electronics is +18 dBm.

Tables 3.4.2-2 thru 3.4.2-5 show the level analysis for transponder in gain states 1 thru 4. In all cases, the noise level and maximum transmit signal level is below the corresponding 1 dB compression points. As the received input signal gets large enough to cause non-linearities, the nonlinearities start to occur first at the output amplifiers A6 and A7, followed shortly by the A5 amplifier. Bandpass filters FL3 and FL2 are used to reject all out of band intermodulation products caused by the non-linearities in A6 and A5 respectively. This minimizes the level of inband the intermodulation products that will be generated by downstream non-linearities.

Item	Part No.	Net Gain (dB)	Output P-1dB (dBm)	BW (MHz)	Cum. Gain (dB)	Equivalent Maximum Input (dBm)	Noise Level (dBm)	Max Tx Level (dBm)
A1	MSA-0670	20	3	1000	20	-17	-61	-23
FL1	TC-302-26-6MM	-4.5	29.5	26	15.5	14	-81	-68
A2	MSA-0670	20	3	1000	35.5	-33	-61	-48
A3	Not Used	0	30	1000	35.5	-6	-61	-48
Pad 1	Not Used	0	30	1000	35.5	-6	-61	-48
A4	MSA-0670	20	3	1000	55.5	-53	-41	-28
Pad 2	5.5 dB	-5.5	24.5	1000	50	-26	-46	-33
A5	MSA-0670	20	3	500	70	-67	-26	-13
FL2	TC-302-30-4MM	-3	30	30	67	-37	-29	-36
M1	SBL-1	-6	-5	1000	61	-66	-35	-42
A6	NE5205	19	8	500	80	-72	-16	-63
FL3	TC-261-26-6MM	-4	29	26	76	-47	-20	-67
A7	MWA-130	14	18	500	90	-72	-6	-53

Table 3.4.1-2. Gain State 4 Level Analysis

Item	Part No.	Net Gain (dB)	Output P-1dB (dBm)	BW (MHz)	Cum. Gain (dB)	Equivalent Maximum Input (dBm)	Noise Level (dBm)	Max Tx Level (dBm)
A1	MSA-0670	20	3	1000	20	-17	-61	-23
FL1	TC-302-26-6MM	-4.5	29.5	26	15.5	14	-81	-68
A2	MSA-0670	20	3	1000	35.5	-33	-61	-48
A3	Not Used	0	30	1000	35.5	-6	-61	-48
Pad 1	8 dB	-8	22	1000	27.5	-6	-69	-56
A4	MSA-0670	20	3	1000	47.5	-45	-49	-36
Pad 2	7.5 dB	-7.5	22.5	1000	40	-18	-56	-43
A5	MSA-0670	20	3	500	60	-57	-36	-23
FL2	TC-302-30-4MM	-3	30	30	57	-27	-39	-46
M1	SBL-1	-6	-5	1000	51	-56	-45	-52
A6	NE5205	19	8	500	70	-62	-26	-73
FL3	TC-261-26-6MM	-4	29	26	66	-37	-30	-77
A7	MWA-130	14	18	500	80	-62	-16	-63

Table 3.4.1-3. Gain State 3 Level Analysis

Item	Part No.	Net Gain (dB)	Output P-1dB (dBm)	BW (MHz)	Cum. Gain (dB)	Equivalent Maximum Input (dBm)	Noise Level (dBm)	Max Tx Level (dBm)
A1	MSA-0670	20	3	1000	20	-17	-61	-23
FL1	TC-302-26-6MM	-4.5	29.5	26	15.5	14	-81	-68
A2	MSA-0670	20	3	1000	35.5	-33	-61	-48
A3	Not Used	0	30	1000	35.5	-6	-61	-48
Pad 1	Not Used	0	30	1000	35.5	-6	-61	-48
A4	Not Used	0	30	1000	35.5	-6	-61	-48
Pad 2	5.5 dB	-5.5	24.5	1000	30	-6	-66	-53
A5	MSA-0670	20	3	500	50	-47	-46	-33
FL2	TC-302-30-4MM	-3	30	30	47	-17	-49	-56
M1	SBL-1	-6	-5	1000	41	-46	-55	-62
A6	NE5205	19	8	500	60	-52	-36	-83
FL3	TC-261-26-6MM	-4	29	26	56	-27	-40	-87
A7	MWA-130	14	18	500	70	-52	-26	-73

Table 3.4.1-4. Gain State 2 Level Analysis

Item	Part No.	Net Gain (dB)	Output P-1dB (dBm)	BW (MHz)	Cum. Gain (dB)	Equivalent Maximum Input (dBm)	Noise Level (dBm)	Max Tx Level (dBm)
A1	MSA-0670	20	3	1000	20	-17	-61	-23
FL1	TC-302-26-6MM	-4.5	29.5	26	15.5	14	-81	-68
A2	MSA-0670	20	3	1000	35.5	-33	-61	-48
A3	Not Used	0	30	1000	35.5	-6	-61	-48
Pad 1	Not Used	0	30	1000	35.5	-6	-61	-48
A4	Not Used	0	30	1000	35.5	-6	-61	-48
Pad 2	15.5 dB	-15.5	14.5	1000	20	-6	-76	-63
A5	MSA-0670	20	3	500	40	-37	-56	-43
FL2	TC-302-30-4MM	-3	30	30	37	-7	-59	-66
M1	SBL-1	-6	-5	1000	31	-36	-65	-72
A6	NE5205	19	8	500	50	-42	-46	-93
FL3	TC-261-26-6MM	-4	29	26	46	-17	-50	-97
A7	MWA-130	14	18	500	60	-42	-36	-83

Table 3.4.1-5. Gain State 1 Level Analysis

3.4.2. Stability Analysis

To prevent the transponder from self oscillating, the net open loop must be less than unity at any single frequency. This means that the net transponder gain less the diplexor isolation must be less than unity at all frequencies. The transponder electronics provides a frequency conversion, however signal frequency at the input of the mixer is always present at the output of the mixer due to the mixer leakthrough. Thus there always exist a net gain from transponder input to output at any single frequency. The frequencies that are going to have the largest net gain will be between the transmit and receive frequency band. Table 3.4.2-1 shows the open loop gain analysis for the transponder, when it is in gain state 5 (maximum gain).

	270 MHz	281 MHz	293 MHz	
Net Elec. Gain (dB) GS5	100	100	100	
Mixer Leakthru (less CL)	20	20	20	SBL-1
Diplexor IL (dB) Tx	1.5	1.5	1.5	
Diplexor IL (dB) Rx	1.5	1.5	1.5	
Diplexor Rej (dB) Tx	0	36	64	DP-261-18-6AA
Diplexor Rej (dB) Rx	58	34	0	DP-302-18-6AA
FL1 Rej (dB)	40	24	0	TC-302-26-6MM
FL2 Rej (dB)	24	10	0	TC-302-30-4MM
FL3 Rej (dB)	0	14	34	TC-261-26-6MM
Net Gain (dB)	-45	-41	-21	

Table 3.4.2-1. Stability Analysis

The mixer RF to IF isolation is typically ≈26 dB at theses frequencies for the mixer selected. However, since 6 dB of mixer conversion loss was used in the net gain component of the budget, a mixer leakthrough value of 20 dB was used. From the table, it is clear that the net open loop gain is much less than unity in the frequency range of 270 to 293 MHz. For frequencies above this range, the rejection of the Tx diplexor filter and FL3 will be greater than that indicated in the tables yielding net gain < -21 dB. For frequencies below 270 MHz, the rejection of the receive diplexor filter, FL1 and FL2 will be greater than the values shown in the table, yielding net gains <-45 dBm. Thus the transponder design is stable and will not self oscillate.

Another stability issue is self oscillation within a portion of the circuitry. There is always a feedback path from every point in the circuit to every other point in the circuit by means of conducted or radiated EMI. To insure stability, we must insure that the loss of all theses feedback paths is greater than the gain of the forward path which closes the loop. For instance, if three 30 dB gain amplifiers are cascaded together to form a 90 dB gain stage, we must insure that the physical isolation from the output of the last amplifer to the input of the first amplifer is greater than 90 dB at all frequencies within the amplifier bandwidth. This 90 dB radiation requirement is not possible at these frequencies without physical shielding (enclosed modules for each amplifer). Sixty dB of EMI suppression within a single module is a more realistic goal that can be acheived with very careful PCB design techniques. We have set a design requirement that no CCA will have a net gain in excess of 50 dB.

3.4.3. Frequency Response Analysis

The analysis providing the net gain and maximum transmit power showed results which are applicable at the center of the frequency band (uplink frequency = 302 MHz). The effects of the frequency response of the diplexor and the three filters within the electronics will reduce the net gain as the uplink frequency deviates from the nominal 302 MHz uplink frequency. This gain reduction is shown in figure 3.4.3-1 as a function of uplink frequency.

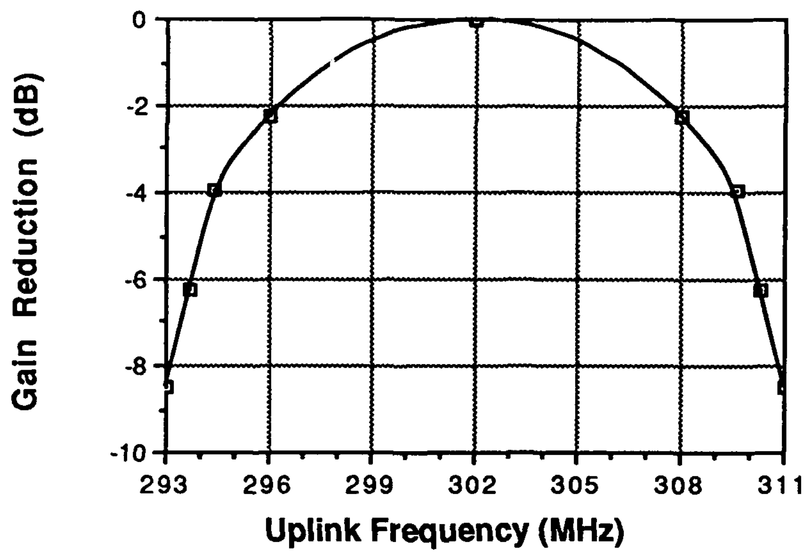


Figure 3.4.3-1. Gain Reduction due to Transponder Frequency Response

Similarly, the maximum transponder output power is reduced as the operating frequency differs from the nominal 302 MHz uplink center frequency. This is due primarily to the frequency response of the transmit portion of the diplexor. This reduction is shown in figure 3.4.3-2.

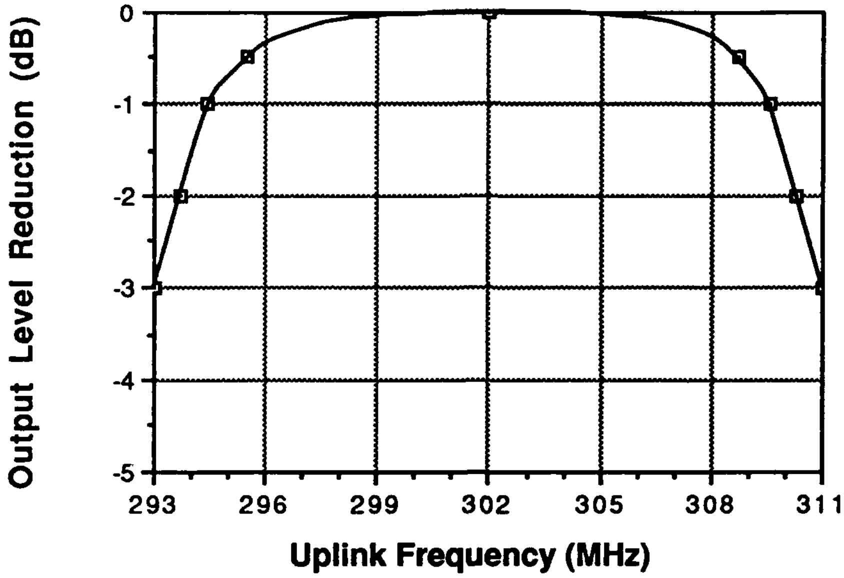


Figure 3.4.3-2. Maximum Output Power Reduction due to Transponder Frequency response

One need not get concerned over the large net gain (>8 dB) variation with frequency because of the following reasons. First, if one knows the net gain reduction for the uplink frequency (this can be accurately determined from empirically data on the transponder), he can compensate his uplink power appropriately. Second, and more importantly, in this system, bandwidth is much more available than power. This means that all users can chose their uplink frequency out of the center of the band. This power limited channel argument will presented in more detail in section 4. But as an example, consider 100 25 kHz channels, each separated by 5 kHz of guard band. This network occupies only 3 MHz of bandwidth. From figure 3.4.3-1, it can be seen that this network of 100 users, each 25 kHz, can be operated in the center of the uplink with less than 0.5 dB gain variation.

3.4.4. Power Consumption

Table 3.4.4-1 shows a current consumption budget when the transponder is in gain state 5 (maximum gain). All active components in the design require a supply voltage of +8V. The results show a total current draw of 208 mA of the +8V supply voltage. As expected, the largest single contributor to the current consumption is the output amplifier, which uses ≈29% of the total current.

Reference Designator	Part #	Current draw (mA)	% of Total
A1	MSA-0670	16	8%
A2	MSA-0670	16	8%
A3	MSA-0670	16	8%
A4	MSA-0670	16	8%
A5	MSA-0670	16	8%
Y1	41 MHz Osc.	30	15%
A6	NE5205	35	17%
A7	MWA-130	60	29%
	Total	205	100%

Table 3.4.4-1. Current Consumption

The battery selected for use in the transponder is a BA-5598/U, which is a military battery. A summary of the specifications are shown in table 3.4.4-2.

Type:	Non rechargeable, Lithium-Sulfer Dioxide
Size:	4.69 x 3.56 x 2.06 (L x W x H)
Weight:	1.50 lb
Output Voltage:	12.0 V
EOL Voltage:	10.0 V
Capacity:	7.2 A-hr

Table 3.4.4-2. Battery Specifications

The output voltage of the battery is regulated to provide an 8 Volt supply which will be constant over the life of the battery. This means that the transponder net gain will not vary as function of time (battery life). The 7.2 A-hr capacity will provide a transponder lifetime of 35.1 hours.

3.4.5. Amplifier Selection Tradeoffs

In the design of the transponder electronics, careful attention was given to the selection of each amplifier. Amplifier selection is critical, since the amplifiers are the primary source of current draw, and the current draw is what limit the lifetime of the transponder. Besides the current draw, there are three critical amplifier specifications, net gain, 1 dB compression point, and noise figure. Listed in table 3.4.5-1, are the specifications of commonly available amplifiers in within the UHF frequency band. Also listed is a figure a merit, the amount of gain per unit mA (dB/ma). This figure of merit is a measure of amplifier gain efficiency, the large the figure of merit, the more desirable the amplifier is for use in the transponder. The amplifiers in the table are sorted by decreasing figure of merit.

Vendor	Part Number	Gain (dB)	NF (dB)	P1 (dBm)	Vcc	Icc (mA)	dB/mA
Avantek	GPD-401	15.5	4.0 dB	-2 dBm	15	10	1.55
Avantek	MSA-0670	20	2.7 dB	3 dBm	> 5 V	16	1.25
Avantek	GPM-552	37	4.5 dB	0 dBm	15	34	1.09
Avantek	MSA-0870	30	2.8 dB	12 dBm	> 10 V	36	0.83
Signetics	NE5205	19	6.5 dB	8 dBm	8	35	0.54
Mini Circuits	MAN-1LN	31	2.8 dB	8 dBm	12 V	60	0.52
Avantek	MSA-470	8.5	6.5 dB	13 dBm	> 7 V	50	0.17

Table 3.4.5-1. Amplifier Tradeoffs

As can bee seen form the table, the amplifiers with the best figure of merit are the GPD-401, MSA-0670. A desirable feature in the amplifiers is that it doesn't need a supply voltage greater than 8 Volts. This requirement eliminates the GPD-401 from consideration. The MSA-0670 also has the best noise figure making it especially desirable for the first amplifier in the chain. The MSA-0670 was used for all amplifiers in the design except the output amplifiers.

The output amplifiers need to have a good 1 dB compression point, since it is this parameter which determines the output power of the transponder. Commonly available amplifiers with good 1 dB compression points are shown in table 3.4.5-2. In this table, the amplifiers are sorted by decreasing output power. The ZHl-1A, ZHL-1042J, and ZFL-100H consume too much current to enable the 24 hr lifetime requirement to be achieved. Although the GPD-405 has a better 1 dB compression point than the MWA-130, the MWA-130 was chosen since it doesn't require a supply voltage above +8 Volts. The Signetics NE5205 was chosen as the amplifier to drive the output amplifier since it has a good tradeoff between 1 dB compression point and gain efficiency, as well the capability to operate from an supply Voltage ≤ 8 Volts (see table 3.4.5-1).

Vendor	Part Number	Gain (dB)	NF (dB)	P1 (dBm)	Vcc	Icc (mA)	dB/mA
Mini Circuits	ZHL-1A	16	11.0 dB	28	24	600	0.03
Avantek	GPD-405	16	6.5 dB	23	15	90	0.18
Mini Circuits	ZFL-100H	31	5.0 dB	20	15	150	0.21
Mini Circuits	ZHL-1042J	25	4.5 dB	20	15	300	0.08
Motorola	MWA-130	14	7.0 dB	18	> 6 V	60	0.23
Avantek	MSA-470	8.5	6.5 dB	13	> 7 V	50	0.17
Avantek	MSA-0870	30	2.8 dB	12	> 10 V	36	0.83

Table 3.4.5-2. Output Amplifier Tradeoffs

3.5. Mechanical

The transponder package, excluding antenna, is 6.00" by 12.5" by 2.125" deep. A top view of the package (cover removed) with components inside is shown in figure 3.5-1. The thick lines in the drawing indicate the sheet metal package. The thinner lines indicate the outline of the various components. The package is built out of 1/16" aluminum with partitions to allow all four of the CCA's to be effectively housed within shielded enclosures.

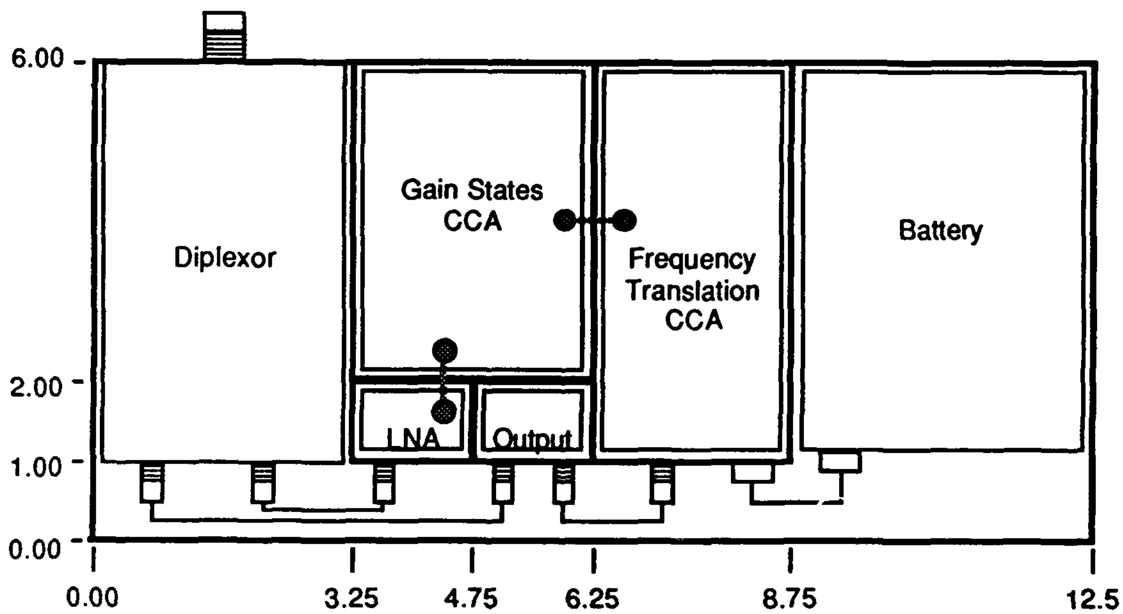


Figure 3.5-1. Transponder Packaging

The diplexor port which shall be connected to the antenna is a type N connector. All RF interconnections within the transponder are shown in the figure. For the most part, the interconnect between the CCA's and diplexor is accomplished with coax cabling between bulkhead SMA connectors that stick out of each individual enclosure. Two RF connections between CCA's are accomplished with PC mount SMA connectors and coax cabling. The partitioning wall shall have a small cutout at the top to enable the coaxial cable interconnection. The power connection between the battery and the frequency translation CCA is provided by a wire harness with a small D type connector. Power distribution to the other CCA's from the frequency translation CCA is accomplished by capacitive feed-thrus within the partitions themselves.

A weight budget for the entire transponder is presented in table 3.5-1. The weight estimate for the mechanical package was determined by estimating the volume of sheet metal within the transponder. The sheet metal is 1/16" thick resulting in a total volume of 16.8 cubic inches. We have increased this number by ≈ 5% (to 17.7 cubic inches, 290 cm^3) to allow for mounting flanges and miscellaneous mounting hardware. The density of aluminum is 2.7 gm/cm^3, producing a mass of 783 gm (1.73 lbs). We have rounded this value upward to 1.75 lbs.

Item	**Weight**	**Justification**
Package	1.75 lb	Estimate (see text)
Battery	1.5 lb	Specification
Antenna	0.5 lb	Specification
Diplexor	1.0 lb	Specification
TCXO	3 oz	Specification
Electronics	4.35 oz	Estimate (see text)
Cables	1.65 oz	Estimate (see text)
Total	**5.3 lbs**	

Table 3.5-1. Transponder Weight Estimate

The heaviest electronic component used is the TCXO which weighs 3 oz. We have budgeted the weight of this item by itself. The weight of the remaining electronics was estimated by determining the total area of the CCA's. RF CCA's in this frequency band, built and designed by ViaSat, have a density between .18 oz/in^2 and .27 oz/in^2. For our estimate we will use a density of .19 oz/in^2. We have selected this number for two reasons: 1) the CCA's involved are most like a existing CCA (equivalent sized connectors, and similar type components) that has a density of .184 oz/in^2, and 2) the component with the largest weight, the TCXO, needs to be removed from the weight estimate to avoid double counting. The total area of all the CCA's is 22.9 in^2, resulting in an weight estimate of 4.35 oz.

The weight of the existing RF cable assemblies with double shielded coax and SMB connectors is 0.33 oz. These cable assemblies are very similar to the SMA cable assemblies used in the transponder. Thus the use of 5 cable assembles results in a weight estimate of 1.65 oz.

4. Communication System Analysis

Section 3 of the report presented the design details and the design analysis of the transponder. This section presents information on how one would use the transponder in a communications system or network. As discussed earlier, the transponder was designed to be compatible with standard UHF radios on the ground segment. The following subsections discuss communication system capabilities, limits, and operational concepts using the transponder and standard UHF radios. To quantify the capabilities, we must first understand the power control concepts that must be employed.

4.1. Power Control

All satellite communication systems using wideband transponders must implement some form of transmit power control. In other words, if we want to maintain a linear transponder, a 100 Watt radio cannot transmit a 100 Watts at the transmitter just because he has the capability to do so. The impact of this would be to surely saturate the transponder. Even if we want to operate the transponder in a saturated state, this might not always be an acceptable thing to do The impact of this would be that the largest signal at the transponder input would get most of the transponder power. The amount of power any given user would get would be a function of how many other users there are, and their levels into the transponder. This creates a "power race" amongst users.

For any type of power control, there are two requirements. First, someone needs to manage the network. This consist of network planning and allocation of maximum transponder output powers that each user would be allowed to use. This can be done by apriori planning and dissemination of allocated powers, transponder altitude, and gain state information to potential users. The second aspect of power control, is that each user must be able to adjust it's output power to a predefined level. If the radio doesn't have output power level adjustment capability, this can be done with a power meter and step attenuator external to the radio. Given these two capabilities, we now present three types of power control that can be used with the transponder.

The first type of power control is what we shall call open loop, unknown ephemeris power control. The transmitter does not know where he is physically located with respect to the transponder. This could be a result of not knowing his own position or not knowing the position of the transponder. However, it assumed that the altitude (approximate) of the transponder and gain state of the transponder is known. If the ground transmitter were given guidelines to use no more than x dBm of transponder output power, he would set his transmit power to achieve this based upon the best case uplink (lowest loss) path loss that could be obtained. That would insure that all other positions would result in a lower transponder output power usage. As an illustrative example, suppose a transmitter were given guideline to use no more than 0 dBm transponder output power (defined at output of the transponder electronics) for a transponder that was at 70,000' and operating in gain state 4. The uplink path loss plus transponder antenna and diplexor losses are presented in table 4.1-1 for a transponder at 70,000' at an uplink frequency of 293 MHz. As can be seen the best case UL loss is ≈ 115 dB at an elevation angle of ≈40°. The transmitter would then assume the UL loss, and compute his maximum uplink EIRP to be 25 dBm, 0 dBm (output power) - 90 dB (net gain) + 115 dB (UL losses). Using a 6 dBi antenna, he would then set his attenuator such that the output power was < +19 dBm (≈80 mW). This would insure that he would never use more than 0 dBm transponder output power at any relative positioning. The uplink path loss plus transponder antenna and diplexor losses are shown for altitudes of 10,000, 30,000 and 100,000 ft in tables 4.1-2 through 4.1-4 respectively.

	Elevation Angle (°)									
	5	10	20	30	40	50	60	70	80	90
Distance (km)	208.6	118.0	62.2	42.9	33.4	28.1	24.9	22.9	21.9	21.5
Path Loss (dB)	128.2	123.2	117.7	114.4	112.3	110.7	109.7	109.0	108.6	108.4
Rx Ant. Gain (dBi)	2.1	2.0	1.4	0.4	-1.0	-2.9	-5.4	-9.0	-15.1	-20.0
Diplexor Loss (dB)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Net UL Loss (dB)	-127.6	-122.8	117.8	-115.5	-114.8	115.2	-116.6	119.5	-125.2	-129.9

Table 4.1-1. Uplink Losses for 70,000' Transponder Altitude

	Elevation Angle (°)									
	5	10	20	30	40	50	60	70	80	90
Distance (km)	34.3	17.6	9.0	6.1	4.8	4.0	3.6	3.3	3.1	3.1
Path Loss (dB)	112.5	106.7	100.8	97.6	95.4	93.9	92.8	92.1	91.7	91.5
Rx Ant. Gain (dBi)	2.1	2.0	1.4	0.4	-1.0	-2.9	-5.4	-9.0	-15.1	-20.0
Diplexor Loss (dB)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Net UL Loss (dB)	-111.9	106.2-	101.0	-98.7	-97.9	-98.3	-99.7	-102.6	108.3-	113.0

Table 4.1-2. Uplink Losses for 10,000' Transponder Altitude

	Elevation Angle (°)									
	5	10	20	30	40	50	60	70	80	90
Distance (km)	97.5	52.0	26.8	18.4	14.3	12.0	10.7	9.8	9.4	9.2
Path Loss (dB)	121.6	116.1	110.4	107.1	104.9	103.4	102.3	101.6	101.2	101.1
Rx Ant. Gain (dBi)	2.1	2.0	1.4	0.4	-1.0	-2.9	-5.4	-9.0	-15.1	-20.0
Diplexor Loss (dB)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Net UL Loss (dB)	-121.0	-115.6	110.5	-108.2	107.4	-107.8	-109.3	112.1	-117.8	122.6

Table 4.1-3. Uplink Losses for 30,000' Transponder Altitude

	Elevation Angle (°)									
	5	10	20	30	40	50	60	70	80	90
Distance (km)	282.4	165.3	88.4	61.1	47.7	40.1	35.5	32.7	31.2	30.8
Path Loss (dB)	130.8	126.1	120.7	117.5	115.3	113.8	112.8	112.1	111.7	111.5
Rx Ant. Gain (dBi)	2.1	2.0	1.4	0.4	-1.0	-2.9	-5.4	-9.0	-15.1	-20.0
Diplexor Loss (dB)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Net UL Loss (dB)-	130.2	-125.7	-120.8	-118.6	-117.9	-118.2	-119.7	-122.6	-128.3	-133.0

Table 4.1-4. Uplink Losses for 100,000' Transponder Altitude

The major drawback with this form of power control, is that each user is only reaching his allocated portion of the transponder power when he is in a best case position of ≈40° elevation angle. Most of the time this will not be the case and the user will be only using a fraction of his allocated transponder power. To see this consider a bunch of users uniformly distributed over the coverage area. Figure 4.1-1 show the expected percentage of users that will have the shown elevation angles. As would be expected, there are many more users with small elevation angles than large elevation angles.

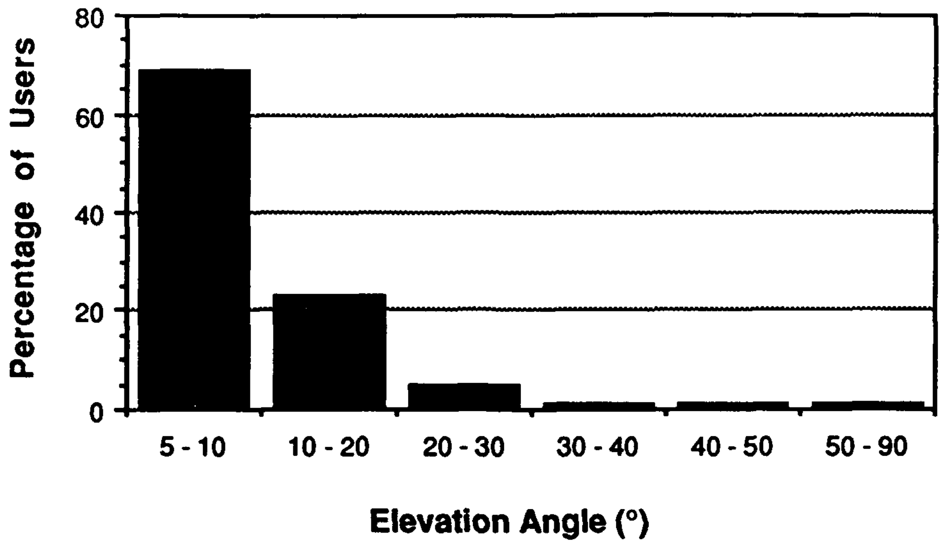


Figure 4.1-1. Distribution of User Elevation Angles using a Transponder Altitude of 70,000'

From table 4.1-1, users with a elevation angle of between 30 and 50 degrees achieve this best case uplink propagation. From Figure 4.1-1, less than 5% of the users lie within this 30 to 50 degree elevation angle range,thus less than 5% of all users will actually use all of the transponder power allocated them. This result can be further quantified by examining the distribution of additional uplink losses that users will experience. Zero dB additional uplink loss is defined as the best case uplink. The percentage of users that experience additional uplink losses vs additional uplink loss is shown in figure 4.1-2. As can be seen, only 3% of the users will come with 1 dB of their allocated portion of the transponder power and over 60% of the users will fall at least 8 dB short of the allocated transponder power.

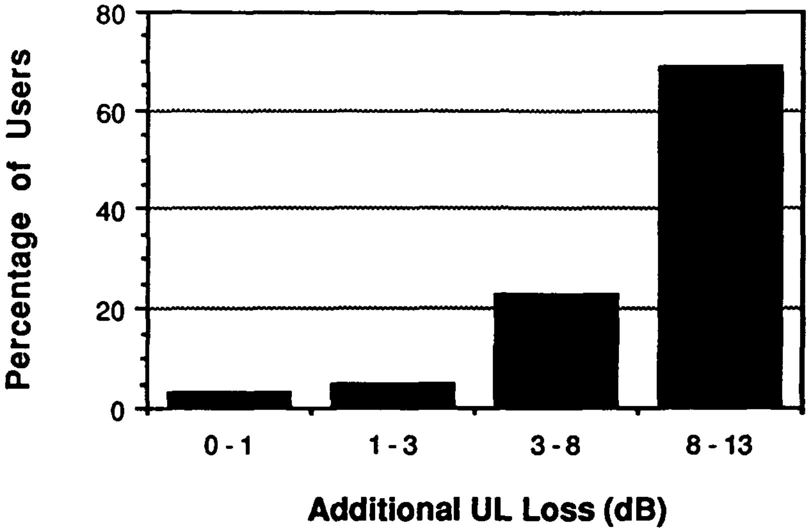


Figure 4.1-2. Distribution of User Additional Uplink Losses Using a Transponder Altitude of 70,000'

A better form of power control is what we call open loop power control with known ephemeris. In this case, each user knows the position of the transponder with respect to himself. This can be accomplished by knowledge of both transponder location and his own location. In this type of power control, the users computes his elevation angle and distance to transponder based upon the known ephemeris data. From this he can compute his uplink losses and set his transmit power appropriately. As an illustration, consider the previous example but it is now known that the elevation angle to the transponder is 5°. From table 4.1-1, his uplink path loss is ≈128 dB. Given the transponder gain state, he computes his uplink EIRP as 0 dBm (desired transponder output) - 90 dB (gain state 4) +128 dB (UL path loss) = 38 dBm. Using a 6 dBi antenna, he sets his attenuator to produce a 32 dBm output (≈1.6 Watts). This form of power control has the advantage that all users will reach their full allocated transponder power.

Yet another approach to power control is what we shall call closed loop power control. In this approach, a user effectively measures the uplink losses by transmitting a signal to himself. He accomplishes this by measuring the signal to noise ratio of the received probe. He then computes the transmit power he needs to reach his allocated transponder power. This technique requires a user with a full duplex radio and the capability to measure the signal to noise ratio. The details of this techique are provided below.

For a given ground station transmit power, P_t, the measured signal to noise ratio is given by,

$$SNR = \frac{P_t \cdot G_{tx} \cdot NG \cdot G_{rx}}{L_{ul} \cdot L_{dl} \cdot kT_{290} \cdot NF \cdot BW} \quad (4\text{-}1)$$

where,

- P_t : Ground transmitter output power in Watts
- G_{tx}: Ground transmit antenna gain
- NG: Net electronic gain of the transponder
- G_{rx}: Ground receive antenna gain
- L_{ul}: Net uplink losses, consisting of propagation loss, Transponder antenna gain, diplexor losses etc. Since this item is a loss (shown in denominator) it will be larger than 1.
- L_{dl}: Net downlink losses, consisting of propagation loss, Transponder antenna gain, diplexor losses etc. Since this item is a loss (shown in denominator) it will be larger than 1.
- k: Boltzmann's constant
- T_{290} Sky noise temperature, assumed to be 290°K
- NF: Receiver Noise Figure
- BW: The bandwidth, in Hz, of the signal to noise ration pre-detection filter

All gain quantities in Eq. 4-1 are linear (not in dB). This expression holds when the communication system is downlink limited, which is always the case (see section 4.2).

Since the ground station is transmitting to itself, the UL losses will be very nearly identical to the DL path losses. Similarly the ground station Rx antenna gain will be very nearly identical to the Tx antenna gain. The only difference in these quantities is due to the frequency difference. But this relative difference is known, thus we can establish the following relationship

$$\frac{G_{tx}}{L_{ul}} = \alpha \cdot \frac{G_{rx}}{L_{dl}} \quad (4\text{-}2)$$

where α is a known, and very close to unity, quantity. Using this in Eq. 4-1 yields,

$$SNR = \frac{P_t \cdot NG \cdot \alpha}{kT_{290} \cdot NF \cdot BW} \cdot \left(\frac{G_{tx}}{L_{ul}}\right)^2 \tag{4-3}$$

The objective of the power control is for the ground transmitter to find some transmit power P_t^*, such that the following holds

$$P_t^* \cdot NG \cdot \frac{G_{tx}}{L_{ul}} = K \tag{4-4}$$

where K is a constant equal to the desired transponder output power in Watts. Eq. 4.3 can be solved for $\frac{G_{tx}}{L_{ul}}$ as a function of SNR, NG, α, kT_{290}, NF, P_t and BW, all known quantities. The result can be inserted into Eq. 4-4, which is then solved for P_t^*, the desired transmit power setting.

To implement this form of power control, each user needs to know the values of the following parameters: NG, α, kT_{290}, NF, P_t and BW. Of these parameters, the only ones that are not obviously known are P_t and NF. P_t can be accurately measured with a power meter and the noise figure of the radio, NF, can be calibrated. The only other concern is with the assumption of the sky noise temperature being 290°K. If one has other knowledge of the sky noise temperature, either empirical or otherwise, the equations can be modified to take advantage of this information.

There are three major advantages of this approach to power control as compared to open loop, known ephemeris power control.

1) The ground transmitter antenna gain, and uplink losses do not need to be known. The latter implies that the relative position and altitude of the transponder need not be known.

2) Closed loop power control is insensitive to additional path attenuation which is not accounted for in the model. This attenuation might be cable losses, pointing errors, or rain attenuation. If there is an additional 3 dB of such attenuation, open loop power control will yield solution 3 dB short of the desired transponder power. Closed loop power control will still arrive at the correct solution.

3) All forms of power control need to accurately know the transponder net electronic gain. Closed loop power control is less sensitive to inaccuracies in the parameter. For example, suppose the actual transponder gain were 2

dB below its advertised value for a given gain state. Open loop power control would yield a solution which is 2 dB in error, where as closed loop power control would yield a solution which is only 1 dB in error.

The disadvantage of closed loop power control is the complexity involved. It requires a full duplex radio with capability to measure signal to noise ratio[2]. It is not clear that any off the shelf radio currently have such a capability. But in any, case closed loop power control is an effective technique that can be incorporated into existing radios and designed into future radios.

For the remainder of section 4, the analysis and link budgets presented will assume some form of efficient power control. Open loop power control with known ephemeris and closed loop power control are two such techniques which will enable the capabilities of the following sections to be achieved.

4.2. Maximum Aggregate Throughput

As can be seen in the link budgets presented in section 4.3, all communication circuits using the transponder will be downlink limited. This means that the received signal to noise ratio on the downlink is much less than the signal to noise ratio on the uplink. The reason for this is very simple. The uplink signal originates from a radio capable of transmitting 1 to 100 Watts. This coupled with a 6 dBi antenna gain produces a EIRP of 36 to 56 dBm per link. The transponder on the output is only capable of generating +18 dBm total power, and this is when it is in a saturated state. Consider a network of 10 users and the transponder operating in a linear (6 dB backoff) state. Using 2 dBm electronics power per user (+12 dBm total power), 1.5 dB diplexor insertion loss, and 2 dB antenna gain yields a downlink signal EIRP of 2.5 dBm per link. Thus the received power on the uplink will always be greater than the received power on the downlink.

The impact of this is that one can easily determine the capacity of the system by only examining the downlink. This analysis is presented in table 4.2-1, for the transponder operating in a linear state and all users implementing power control.

[2] Such a measurement might be made by measuring the Bit Error Rate of the link and mapping that into a received E_b/N_o based on a calibrated lookup table.

	Transponder Altitude			
	10,000 ft	30,000 ft	70,000 ft	100,000 ft
Desired xponder Output (dBm)	12.0	12.0	12.0	12.0
Diplexor IL (dB)	1.5	1.5	1.5	1.5
Xponder Tx Antenna (dBi)	2.1	2.1	2.1	2.1
Distance (km)	34.3	97.5	208.6	282.4
Tx Frequency (MHz)	270.0	270.0	270.0	270.0
Path Loss (dB)	111.8	120.8	127.5	130.1
DL Margin (dB)	3.0	3.0	3.0	3.0
Rx Antenna Gain (dBi)	6.0	6.0	6.0	6.0
DL Polarization Loss (dB)	3.0	3.0	3.0	3.0
Radio NF (dB)	5.0	5.0	5.0	5.0
DL C/No (dB-Hz)	**69.8**	**60.8**	**54.1**	**51.5**
Required Eb/No (dB)	6.0	6.0	6.0	6.0
Aggregate Data Rate (kbps	**2413.7**	**298.7**	**65.3**	**35.6**

Table 4.2-1. Maximum Aggregate Data Rate for Linear Transponder

In the link budget a worst case elevation angle of 5° was used, but this is also the most likely elevation angle. The required radio E_b/N_0 is 6 dB. This is chosen based upon coherent PSK modulation with k=7, r=1/2 coding, 1.5 dB implementation loss, operating at a BER of 10^{-5}.

The link budget also includes a link margin of 3 dB. Even though the 3 dB loss is shown in the downlink, it could in fact occur entirely in the uplink or some in the downlink and some in the uplink as long as the total loss is ≤ 3 dB. For open loop power control, it makes no difference where the additional loss occurs. For example, suppose it is all in the downlink, then the number in the table apply exactly. If it is all in the uplink, the actual transponder output power will 3 dB less than the 12 dBm shown in the table, however, there would be no downlink loss (shown as downlink margin) resulting in the same received C/N_0. For closed loop power control scheme, any additional losses in the uplink would be removed by the power control approach. However, this would not help any additional attenuation in the downlink. For the worst case scenario, where all additional losses are in the downlink, the aggregate throughput would be as shown in the table.

The aggregate data rate shown in table 4.2-1, is the data rate sum of all the links. For instance, the 65.3 kbps aggregate rate for a 70,000' altitude transponder could be implemented as a single 64 kbps link, or 27 voice links at 2400 bps each, or 108 links at 600 bps each, or 870 links at 75 bps each. It can also be implemented as any combination of data rates such that the total is less than 65.3 kbps. The aggregate throughput can also be increased by operating the transponder in a saturated state. In this case the transponder output power would be +18 dBm, yielding a maximum aggregate data rate which is a factor of four larger than those shown in the table. However, in this scenario one must determine the impact of the intermodulation products and distortion on each of the individual links.

Another observation is power bandwidth tradeoff. For this system power is a very scarce resource but bandwidth is in abundance. Consider the 2.4 Mbps aggregate data rate for a 10,000' altitude transponder. At a bandwidth usage of 1 bps/Hz, this throughput would only require 2.4 MHz of bandwidth, however the transponder bandwidth is 18 MHz. At higher payload altitudes,the power limited nature of the channel in even more apparent.

4.3. System Operational Planning

System planning is performed by the central management facility. Its function is to take network operational requirements, such as number of users, data rates, transmitter EIRP characteristics, and radius of coverage and determine operating concepts such as transponder altitude, transponder gain state, and transponder power allocations per link. This process is best depicted with some examples.

As a first example consider an operational requirement to provide up to 100 users within a 50 nmi radius a 2400 bps voice capability. Each user shall have a 1 Watt radio with a 6 dBi circulary polarized antenna. The first step is to determine the transponder altitude. The geometry for this process is shown in figure 4.3-1.

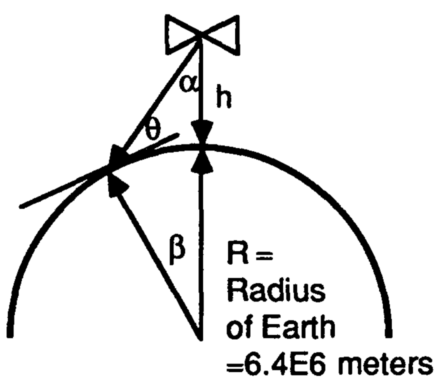


Figure 4.3-1. Link Geometry

The coverage radius, r_c, is determined from the following equation,

$$r_c = R \cdot \left\{ \cos^{-1}\left[\frac{R\cos(\theta)}{R + h} \right] - \theta \right\} \quad (4\text{-}5)$$

where, R, h, and R_c are of the same units and θ is the minimum look angle of 5°. For a r_c of 50 nmi, one must solve Eq. 4-5 for h with $\theta = 5°$. Performing this yields a minimum altitude, h, of 28,816 feet. Thus we shall select a transponder altitude of 30,000 feet.

We then must select a transponder net gain such that,

$$P_{max} + G_t - L_{ul} + NG \geq P_{out} \quad (4\text{-}6)$$

where P_{max} is the maximum ground transmit power in dBm (30 dBm for this example), G_t is the ground terminal antenna gain, 6 dBi, L_{ul} is the sum af all uplink losses in dB, NG is the transponder net gain in dB, and P_{out} is the desired transponder electronics output per user, in dBm. Assuming we want to operate the transponder in its linear region, the total output power needs to be +12 dBm. To support 100 users, each user will get -8 dBm, thus this is the value for P_{out}. We can determine the L_{ul} in the following way,

$$L_{ul} = L_{path} + L_{diplexor} + L_{pol} - G_{antenna} \quad (4\text{-}7)$$

where $L_{diplexor}$ is the diplexor insertion loss (1.5 dB), L_{pol}, is the polarization loss for the transponder antenna (3 dB), and we must select value for the free space path loss, L_{path}, and the transponder antenna gain, $G_{antenna}$, that maximize the total uplink losses. From the uplink loss table presented in section 4.1, this occurs at a look angle of five degrees.[3] Thus, for this elevation angle we use an antenna gain, $G_{antenna}$, of 2.1 dB and the free space path loss is computed from the following equation:

$$L_{path} = 37.8 + 20\log(f) + 20\log(d) \text{ dB} \quad (4\text{-}8)$$

where f is the frequency in MHz, and d is the path distance in nautical miles. The path distance is computed from the following equations (see figure 4.3-1)

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[3] The table actually show a slightly large uplink loss with a look angle of 90°, but this is a pathological case since there is essentially zero probability that a user will be directly under the transponder.

$$d = \sqrt{R^2 + (R + h)^2 - 2R(R+h)\cos(\beta)} \quad (4\text{-}9)$$

$$\beta = \cos^{-1}\left[\frac{R\cos(\theta)}{R + h}\right] - \theta \quad (4\text{-}10)$$

where θ is the worst case elevation angle, 5°, and R and h are in nmi. Using a transponder altitude of 30,000 feet (4.94 nmi) and an uplink frequency of 311 MHz, we get a worst case free space path loss of 122 dB. Using this in Eq. 4.7 generates an uplink loss of 124.4 dB. Inserting this value into Eq. 4-6 and solving for NG yields NG $\geq$ 80.4 dB, thus we shall use a net gain of 90 dB implying the transponder operates in gain state 4.

At this point we have done all the required system planning. The results yielded an altitude of 30,000', transponder gain state of 4, and transponder power (defined at the output of the transponder electronics) allocation of -8 dBm. Each user can employ one of the two efficient power control techniques to adjust his output power level, but this power level will always be less than 1 Watt.

A complete link budget for this planned network is shown in table 4.3-1. This budget is performed at a uplink frequency of 302 MHz, for a user with a 5° elevation angle. This link budget results in a link margin of 4.2 dB.

Parameter	Value	Notes
Radio Tx Power (dBm)	20.2	Set by Power Control
Tx Ground Antenna Gain (dBi)	6.0	
UL Path Loss (dB)	121.8	5° Elevation Angle
Xponder Antenna Gain (dBi)	2.1	5° Elevation Angle
Polarization Loss (dB)	3.0	Circular to Linear
Xponder Diplexor Loss (dB)	1.5	
Xponder NF (dB)	3.0	
UL C/No (dB-Hz)	**73.0**	
Xpndr Electronic Gain (dB)	90.0	Gain State 4
Xpndr Output Power (dBm)	-8.0	
Diplexor Loss (dB)	1.5	
Xponder Antenna Gain (dBi)	2.1	5° Elevation Angle
DL Path Loss (dB)	120.6	5° Elevation Angle
Rx Ground Antenna Gain (dBi)	6.0	
Polarization Loss (dB)	3.0	Linear to Circular
Radio NF (dB)	5.0	Typical UHF Radio Value
DL C/No (dB-Hz)	**44.0**	**Down Link Limited**
Available C/No (dB-Hz)	**44.0**	
Desired Data Rate (bps)	2400.0	
Req. Eb/No (dB)	6.0	Coherent PSK, w/FEC
Req. C/No (dB-Hz)	**39.8**	
Link Margin (dB)	**4.2**	
% of Transponder Power	**1.00%**	**per User**
Max # Users	**100**	**Planned Value**

Table 4.3-1. Example #1 Link Budget

As another illustrative example, consider a planned network of 50 users, each 1200 bps, spread over a coverage radius of 100 nmi. These users will have a 6 dBi circularly polazrized transmit antenna and be allowed to transmit as much as 20 Watts, but no more. Using Eq. 4-5, we see that the minimum transponder altitude is 62,126 feet. We shall us 70,000'. Operating the transponder in its linear region we need an total P_{out} of +12 dBm. Supporting 50 users yields a P_{out} of -5 dBm per user. Using Eq. 4-8, 4-9, and 4-10, we compute a maximum uplink path loss of 128.7 dB at 311 MHz. Using Eq. 4-7, yields a total uplink loss, L_{ul}, of 131.1 dB. Finally, the minimum net gain of 77.1 dB can be determined by solving Eq. 4-6 for NG. Thus we select transponder gain state 3, which has a net gain of 80 dB. The link budget for the resultant network appears in table 4.3-2.

Parameter	Value	Notes
Radio Tx Power (dBm)	39.8	Set by Power Control
Tx Ground Antenna Gain (dBi)	6.0	
UL Path Loss (dB)	128.4	5° Elevation Angle
Xponder Antenna Gain (dBi)	2.1	5° Elevation Angle
Polarization Loss (dB)	3.0	Circular to Linear
Xponder Diplexor Loss (dB)	1.5	
Xponder NF (dB)	3.0	
UL C/No (dB-Hz)	**86.0**	
Xpndr Electronic Gain (dB)	80.0	Gain State 3
Xpndr Output Power (dBm)	-5.0	
Diplexor Loss (dB)	1.5	
Xponder Antenna Gain (dBi)	2.1	5° Elevation Angle
DL Path Loss (dB)	127.2	5° Elevation Angle
Rx Ground Antenna Gain (dBi)	6.0	
Polarization Loss (dB)	3.0	Linear to Circular
Radio NF (dB)	5.0	Typical UHF Radio Value
DL C/No (dB-Hz)	**40.4**	**Down Link Limited**
Available C/No (dB-Hz)	**40.4**	
Desired Data Rate (bps)	1200.0	
Req. Eb/No (dB)	6.0	Coherent PSK, w/FEC
Req. C/No (dB-Hz)	**36.8**	
Link Margin (dB)	**3.6**	
% of Transponder Power	**1.98%**	**per User**
Max # Users	**50**	**Planned Value**

Table 4.3-2. Example #2 Link Budget.

5. Summary

This report has presented the design of a 5 lb transponder that can be used with high altitude balloons or unmanned air vehicles. This satellite surrogate can be used to provide UHF satellite communications using existing off the shelf UHF radios. This surogate satellite system can provide communications for more than 100 users over a 100 nmi radius for duration in excess of 24 hours. In addition the wideband architecture will enable operation with larger data rates, as compared to standard UHF SatCom narrowband channels, and spread spectrum systems.